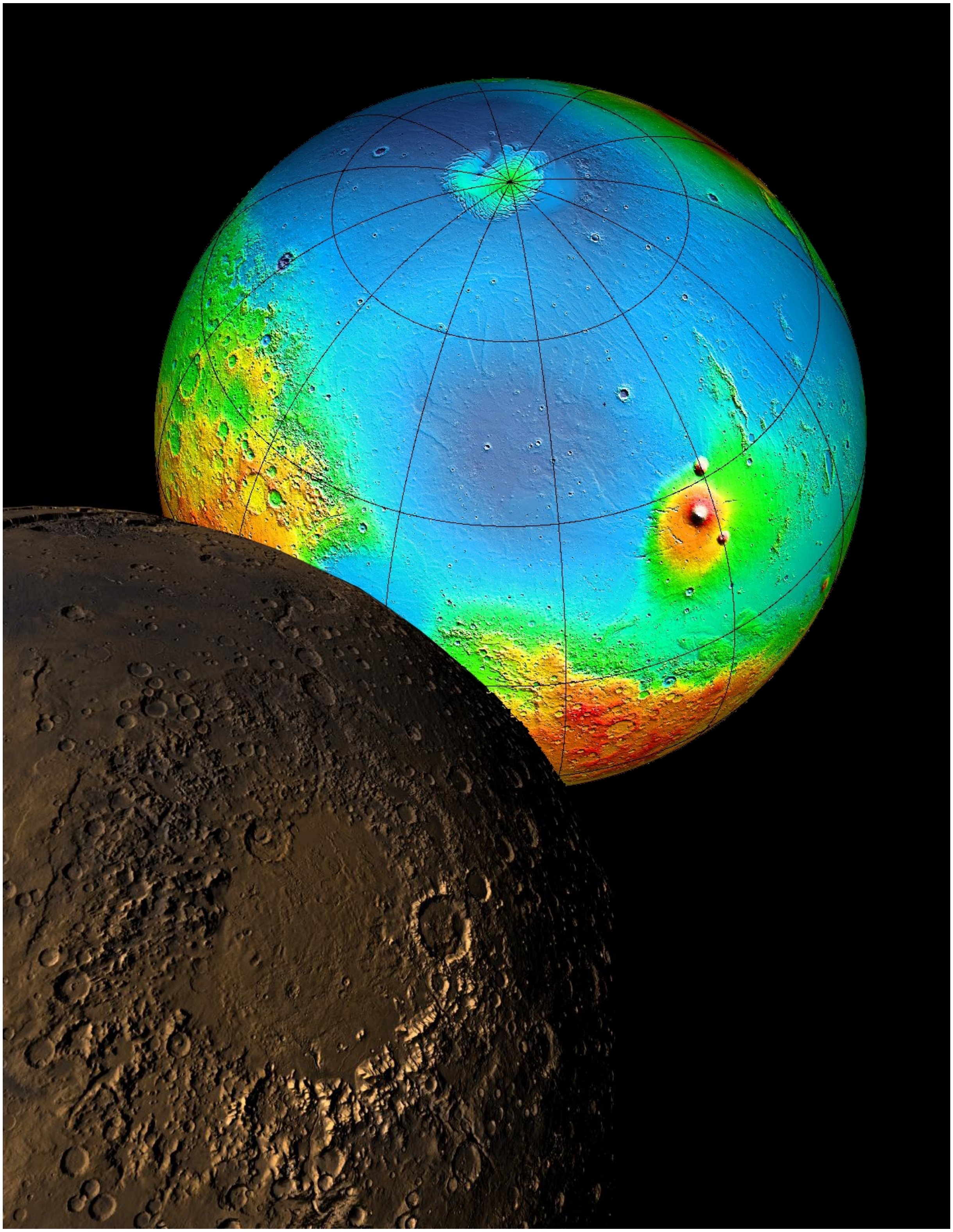

3

Mars: The Evolution of an Earth-like Planet

The first high-resolution images acquired of Mars by the Mariner 4 spacecraft at the dawn of the space age shattered popular notions of Mars. Far from being an oasis, the surface of Mars appeared to be as battered and barren as the Moon. With its thin atmosphere and bitter cold temperatures, Mars was more parched than the driest places on Earth. The prospect that life could have evolved there seemed dim.

Each subsequent mission to Mars has changed that impression in surprising ways. Mariner 9 revealed towering volcanoes, polar caps, and channels apparently cut by water. Systematic observations of the surface and atmosphere by Viking led to a huge increase in our knowledge of the breadth of martian geologic history and the dynamics of the current climate. We had landed on the surface for the first time. Data from the recent Mars Global Surveyor (MGS) have again revolutionized our understanding of the evolution of the planet (Figure 3.1), revealing the importance of the very early development of Tharsis, discovering huge magnetic anomalies from an early magnetic field, and showing evidence for recent or even ongoing climate change. Fundamental information also has been derived from the study of martian meteorites. Detailed analysis of these samples has invigorated the debate over whether life ever arose on Mars.

Are we alone? is one of the most compelling questions in science. Is the development of life a common occurrence or an event that is exceedingly rare? On Earth, wherever water exists in a liquid state, viable organisms have been found. Mars is probably the most compelling place to attempt to answer the question, Did life ever arise elsewhere in the solar system?, because we know now that water once existed (and under some circumstances may exist today) in a liquid state on the surface of Mars, and it likely exists in a liquid state at depth in the crust. While the pre-space-age vision of civilizations on Mars has been replaced with a more informed understanding through exploration and discovery, Mars is still the most compelling and accessible target in the solar system on which to address the question of life's existence beyond Earth.

A synthesis of these discoveries and the results of scientific analyses show that, like Earth, Mars is a planet of contrasts. Both planets have had complex geologic histories and climates that evolved and changed; in both cases

FIGURE 3.1 *(facing page)* Data from the Mars Orbiter Laser Altimeter (MOLA) instrument on the Mars Global Surveyor spacecraft have enabled the construction of highly accurate images of Mars's topography. These two images show the Red Planet's two dissimilar faces. The northern hemisphere *(upper right)* is flat and lightly cratered. In contrast, the southern hemisphere shows extremes of relief and is heavily cratered. Courtesy of the MOLA team.

liquid water played an important role in the evolution of the surface and creation of an environment hospitable to life. Among the planets, Mars is of particular interest because of its similarity to Earth, yet the most important lessons to be learned stem from the differences between the two planets. Mars science might most usefully be thought of as a study of the evolution of an Earth-like planet.

UNIFYING THEMES FOR STUDIES OF MARS

The exploration of Mars has led us to the point of being able to understand the main elements or components of its systems. The sum total of information from spacecraft and telescope observations and from Earth-based research and analysis programs has led to a fairly complete first-order understanding of the planet: the composition and first-order dynamics of its atmosphere, a broad understanding of its water and climate history, its crustal structure as inferred from global gravity and topography, and its surface and crustal chemistry from remotely sensed measurements and the study of martian meteorites. While the individual component systems of Mars have been illuminated, the relationships between them are less well understood. Research addressing these crosscutting questions or themes has the potential to significantly advance our understanding of Mars as a planet. The themes are as follows:

- Mars as a potential abode of life;
- Water, atmosphere, and climate on Mars; and
- Structure and evolution of Mars.

The first theme recognizes that Mars has had in the past on its surface, and may continue to have today in its subsurface, environments with all the ingredients needed to sustain life. Did life ever arise? and Does it exist today? are important first-order questions. To answer these questions, however, we need to know more about Mars and its evolution. If the answer to questions about life is yes, it will be important to know where, how, and for how long life evolved, and its relationship to the planet's evolution. If the answer is no, then it will be equally important to try to understand why life did not arise. Clearly, the answer will be tied to the second theme, the history of volatiles and evolution of the climate and the atmosphere. One way of addressing the question of life will be by searching for a biological imprint on isotopic systems. But to use this type of approach will require a more complete understanding of the atmosphere, the climate and its history, and, of course, water.

Space exploration has taught us that a strong coupling exists between the structure and evolution of planetary interiors and their atmospheres and climates: that is, between the second and third themes. For example, the discovery of localized, very strong remnant magnetism in its ancient crust suggests that early Mars had an active dynamo and a strong magnetic field. If this was the case, it would have shielded the planet from biologically harmful solar (and cosmic) radiation and inhibited the loss of volatiles (water) to space.

One of the distinctive characteristics of Earth relative to other bodies in the solar system is the presence of life. Over the past decade, we have begun to appreciate that life on Earth has been more than a thin veneer of biology passively enjoying the ride; in fact, life has strongly influenced the evolution of Earth. Clearly Mars is not as biologically active as Earth is, and it may even be inert. However, because Mars preserves part of its ancient geologic record that is now lost on Earth, and because it has an atmosphere, evidence for liquid water at some time on its surface, and an ancient magnetic field, it provides a window into the early history of the evolution of an Earth-like planet and perhaps the origins of life.

MARS AS A POTENTIAL ABODE OF LIFE

Present Life

The surface of Mars today is cold, dry, chemically oxidizing, and exposed to an intense flux of solar ultraviolet radiation. These four factors are likely to limit or even to prohibit life at or near the surface of the martian regolith.

Temperature is of interest not only because of its controlling influence on microbial metabolic rates but also because of its influence on the stability of liquid water. Although the peak daytime surface temperature near the martian equator can rise above the freezing point of water during much of the year, the average surface temperature is about 220 K, well below the freezing point of water. Liquid water is essential for life as we know it. Water is abundant on Mars, but not in liquid form.[1] Water vapor and ice crystals are present in the atmosphere, and water ice is almost certainly present within the martian regolith at high latitudes and at the surface in polar regions. At increasing depth, where the rock is warmer as a result of the planetary geothermal gradient, liquid water may be present in pore spaces.[2]

To date, a single set of robotic studies has searched for extant life on Mars: the Viking life-detection experiments, which were designed to test for organisms that used as their carbon source either carbon dioxide or organic molecules. Though the results obtained by the three sets of experiments are regarded as having shown the materials tested to be devoid of both organic compounds and evidence of life,[3,4] this interpretation has been subject to debate.[5]

The lack of agreement highlights the difficulties inherent in the detection of viable microorganisms by robotic means. Indeed, even were there unanimity that the Viking experiments did not show the presence of life, the experiments could still be criticized as being overly "geocentric" in that they showed a lack of evidence of metabolism only of those types particularly common among terrestrial microbes, not of all conceivable metabolisms (nor even of various redox-reaction-based microbial metabolisms well known on Earth).

The problem of distinguishing between biological and nonbiological organic compounds is also complicated. The carbonaceous chondrites, interplanetary dust particles, and probably other bodies within the solar system contain abundant organic material that is structurally similar to biological products. Definitive resolution of the differences between biotic and abiotic organic molecules requires highly sophisticated techniques well beyond any that could be managed robotically.

The accepted interpretation of results from the Viking landers is that the surface materials tested were devoid of organic molecules and of any other evidence of life.[6] However, even without consideration of alternative interpretations,[7] the Viking results cannot be taken as indicating that life does not currently exist on Mars. Organisms at the Viking sites might have been missed because the experimental conditions (e.g., the nutrients provided or processes followed) were not chosen correctly. Even more importantly, martian life might reside in aqueous oases, such as any recently active volcanic vents or fumaroles distant from the Viking landing sites, or at depths far beneath the surficial regolith sampled by the Viking experiments.

Past Life

The surface environment of Mars may not always have been as hostile to life as it is today. Early in the planet's history, the average temperature may have been warmer and the atmosphere more dense, and liquid water may have existed at the surface. The geomorphologic evidence, especially valley networks, indicates that the martian climate was wetter, warmer, and appreciably more hospitable to life prior to about 3.5 billion years ago than it is at present. Fossil evidence of past martian life, if there was any, may be preserved in surface water-laid deposits such as lake- or streambed sediments, in evaporitic mineral pans,[8] and in hydrothermally deposited mineral crusts (Figures 3.2a and b).

An important zone that seems likely to have been habitable throughout martian history is the crustal subsurface, where water may exist in a liquid state. The geothermal gradient of Mars is probably such that liquid water is present at depths as shallow as 2 km near the equator.[9] The discovery of terrestrial microbes living deep within the Columbia River basalts in the U.S. Pacific Northwest and elsewhere on Earth,[10] at depths as great as 3 km,[11] is consistent with the possible presence of microbes living in similar settings on Mars. Samples from hypothetical subsurface settings of life would be very difficult to access, yet such materials may have been dislodged and brought to the surface by meteoritic impacts.

A study of the martian (SNC) meteorite ALH84001 produced evidence suggestive of biological activity on Mars about 3.6 billion years ago.[12] This conclusion has not been widely accepted; the report has engendered much discussion, both pro and con, regarding each of the several intriguing indicators of life proposed.[13]

FIGURE 3.2a An aerial view of the Grand Prismatic Hot Spring in Wyoming's Yellowstone National Park. The color variations are due to pigments in thermophyllic microbes residing in the waters. Such systems are being studied to understand the limits of life on Earth and as possible analogs for environments where life may have existed on Mars. Image courtesy of Russ Finley, Island Park, Idaho.

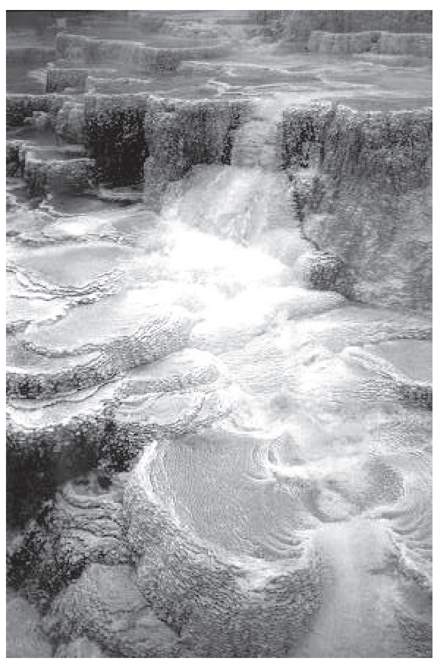

FIGURE 3.2b Travertine deposits at the Minerva Terrace, Mammoth Hot Springs, Yellowstone National Park. Such deposits are intimately associated with microbial communities, aspects of which are commonly preserved in the travertine deposits. Hot springs and their deposits are being studied to understand the limits of life on Earth and as possible analogs for environments where life may have existed on Mars. Image courtesy of Russ Finley, Island Park, Idaho.

Environmental Context for Life

The question of life on Mars must transcend a search for actual organisms. It must include the question of whether the martian environment is or ever was hospitable to the beginning of life. This is a broad and complex question, and the evidence may be so deeply buried in the past that it can be answered only by gaining an extensive and deep knowledge of Mars. For example, on Earth, enzyme-driven metabolic processes can create characteristic biogenic isotopic signatures (affecting, in particular, the ranges of compositions of the stable isotopes of carbon, sulfur, nitrogen, hydrogen, and possibly iron). However, in order to use such isotopic measurements to test for the past presence of life on Mars, we need to know the scope of abiotic fractionating processes there. The search for life should be based on the premise that to understand the potential habitability of Mars, we must fully understand the planet's present and past states. We should be as prepared for a negative answer regarding Mars's potential habitability as for a positive one. The importance of a positive answer is clear, but a negative answer would prompt inquiries into what the implications are for the planetary differences between Earth and Mars.

Key Questions

Questions with potential for a paradigm-altering discovery related to the question of life on Mars include the following:

- Does life currently exist on Mars?
- Did life ever exist there?

A question with potential for a pivotal scientific discovery is—

- How hospitable was and is Mars to life?

Future Directions

The most important future activities with respect to the question of life on Mars are as follows:

1. Sample-return missions will be required to permit definitive tests in terrestrial laboratories for present and past life on Mars (see section "Priorities and Recommendations" below); robotic missions preceding the sample-return missions will assist in locating the most fruitful sites to be sampled.
2. A broad program of study of the Mars environment, present and past, is needed to understand the context in which life did or did not arise on that planet.

WATER, ATMOSPHERE, AND CLIMATE ON MARS

Water

The topics that comprise the theme of water, atmosphere, and climate on Mars are closely linked. As on Earth, water exists on Mars in many states and participates in a broad range of important physical, chemical, and possible biological processes. Water has played a key role in the evolution of the martian climate and in the shaping of Mars's geological history.

The question of where water is on Mars today is difficult to answer fully. We have direct observations of four exposed martian water reservoirs, which include water vapor in the atmosphere, water ice in the atmosphere, seasonal water ice deposits at the surface, and permanent water ice deposits at the polar caps. Of the four, the martian polar caps are by far the most massive. Recent MGS MOLA topographic profiles indicate that the mass of water ice contained within Mars's north and south polar caps, assuming a high ice-to-dust ratio, is the equivalent of a global water layer 22 to 33 m thick.[14]

Beyond the water reservoirs that now can be detected on Mars, there is good reason to suspect the presence of hidden water reservoirs whose combined masses should be much greater than those of the reservoirs that are currently exposed.[15] In Mars's near-surface regolith, it is expected that water is adsorbed on soil particles, and there is fragmentary evidence from the Viking Gas Exchange experiment that the mass fraction of that water could be on the order of 1 percent. Viking and MGS observations have provided geomorphic evidence that the layered deposits surrounding the north and south polar caps also contain water ice, but its mass fraction is currently not well constrained. It is also expected that near-surface ground ice is to be found on Mars, as on Earth, and numerous geomorphological indicators support this idea.[16] Models predict that it should be present within the top meters of the surface at latitudes as low as 20 degrees from the equator in favorable locations.[17]

Because of Mars's low surface temperatures, the partitioning of water is heavily biased toward its condensed phases, causing the martian atmosphere to be extremely dry and ineffective at transporting large quantities of water on seasonal time scales. Liquid water on Mars is not expected to be stable on Mars today, because temperatures exceed 273 K only at low latitudes during the warmest periods of the day, and any liquid generated would quickly evaporate and be transported by the atmosphere to colder locations where it would then freeze.

Some of the most exciting questions concerning Mars deal with the past distribution and behavior of water. Many of these questions are motivated by geomorphic evidence such as runoff channels, outflow channels, and other features that have been interpreted to mean that liquid water may have been present periodically on the surface of Mars in past epochs.[18] The recent MGS Mars Orbiter Camera and Mars Orbital Laser Altimeter observations have provided evidence for large channels that once flowed from the southern highlands to the northern lowlands,[19] widespread ancient layering inferred by some to be of sedimentary origin,[20] and small gullies on crater walls that are considered to be evidence for recent erosion by fluids (Figure 3.3).[21]

Atmosphere

Our knowledge of the composition of the Mars atmosphere is based on measurements of minor gases such as neon, krypton, and xenon and ratios of common isotopes in the ambient atmosphere ($^{36}Ar/^{38}Ar$, $^{12}C/^{13}C$, $^{16}O/^{17}O$, $^{16}O/^{18}O$, $^{14}N/^{15}N$, $^{2}H/^{1}H$) by the Viking descent mass spectrometer, ground-based and airborne spectroscopy, and laboratory analysis of atmospheric gases captured in the vitreous components of martian meteorites. It is thought that a combination of impact erosion and long-term atmospheric loss from the top of the atmosphere by solar-wind sputtering and other processes, and possibly sequestration of CO_2 and other gases in the crust of the planet, are responsible for the present low atmospheric pressure at the surface of Mars (the yearly average is ~6 mbar).

Mars's present-day lower atmosphere is dominated by the behavior of CO_2, water vapor, and dust, as driven by the Mars/Sun configuration and by the interactions of CO_2, water vapor, and dust with the surface. A combination of the above, together with issues of transport and cloud physics, constitutes Mars meteorology. Seasonal changes in the atmospheric mass of CO_2 are up to 30 percent in the current epoch. Water vapor also interchanges with clouds and surface materials; its average annual column abundance is ~10 to 40 precipitable microns of water at north midlatitudes.

Very little is known about the upper atmosphere of Mars. However, the interactions between Mars's upper atmosphere and the impinging solar wind and solar ultraviolet light appear to have played a significant role in the evolution of the martian atmosphere and in the transition from a warmer and wetter environment to the present-day colder and drier environment. Only by understanding the processes that can occur in the upper atmosphere can we fully understand what drove the changes in the volatile inventory and in the climate and thereby understand the evolution of habitability on Mars.

The only in situ measurements of atmospheric composition came from the Viking descent neutral mass spectrometers. These provided two midlatitude vertical profiles, in the altitude range of about 120 to 200 km, of CO_2, CO, N_2, O_2, and Ar densities during low-solar-activity conditions. Using the scale heights thus measured, atmospheric temperature profiles were deduced. These temperatures showed quite large variations and averaged <200 K. Some indirect and limited information on composition and temperatures has been obtained using airglow and ionospheric information. The upper-atmospheric temperatures appear to vary by about 150 K between solar cycle minimum and maximum conditions. The z-axis accelerometer carried by the MGS provided a great deal of important information about total densities and temperatures during its extended aerobraking period.[22]

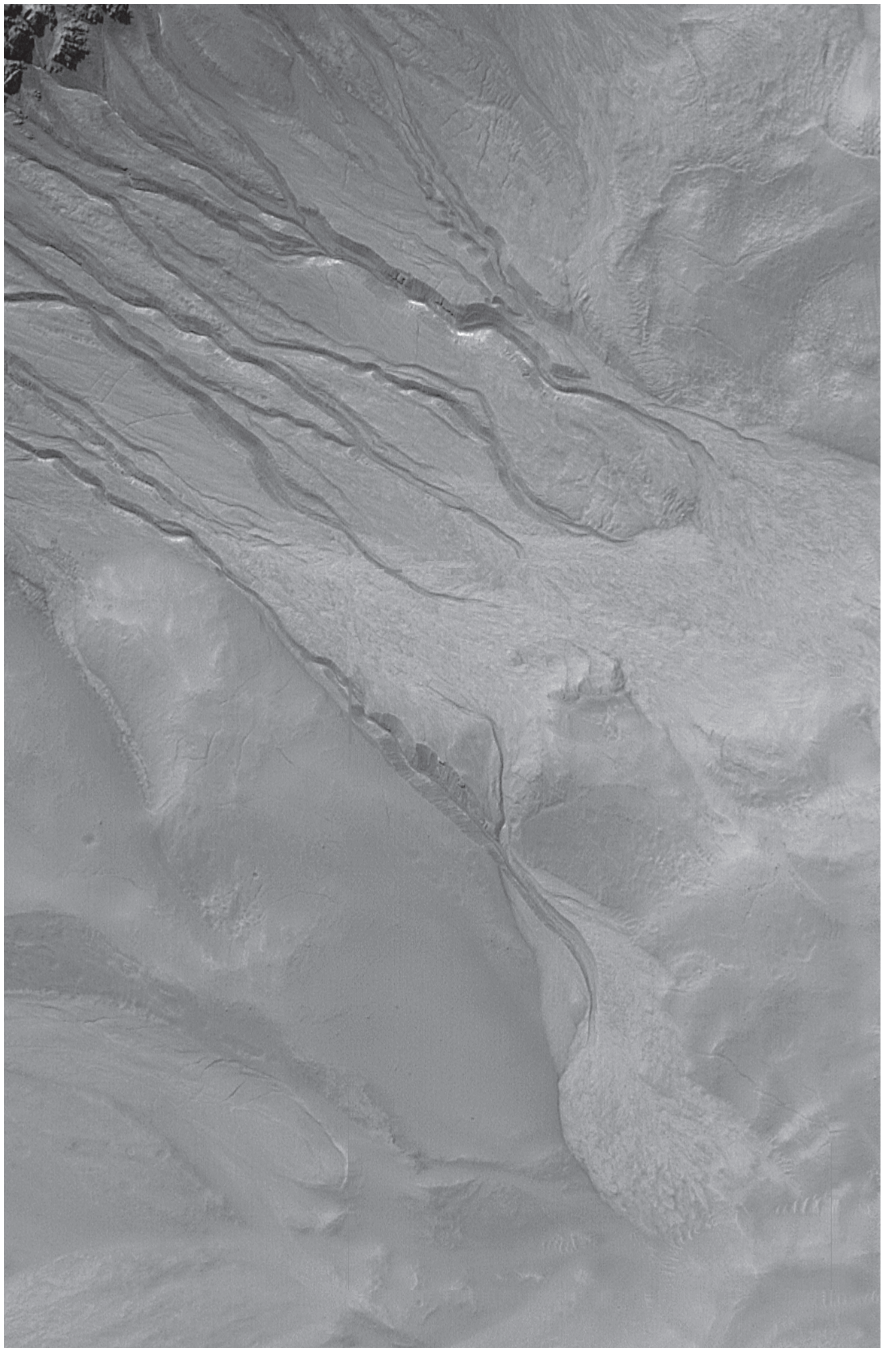

FIGURE 3.3 The Mars Orbiter Camera on Mars Global Surveyor imaged these channels in a crater in the region East Gorgonum (37.4° S, 168.0° W). These features have been interpreted by some researchers as being due to the recent flow of water across the surface. The numerous channels and apron deposits indicate that many tens to hundreds of individual events involving the flow of water and debris have occurred here. The channels and aprons have very crisp, sharp relief, and there are no small impact craters on them, suggesting that these features are extremely young relative to the 4.5-billion-year history of Mars. The image is 2.3 km wide, and illumination is from the upper left. Mars Global Surveyor, Mars Orbiter Camera, Release No. MOC2-241, courtesy of NASA/JPL/Malin Space Science Systems.

The only in situ measurements of the thermal plasma composition, density, and temperature in the ionosphere of Mars were obtained by the retarding potential analyzers carried aboard the two Viking landers, along with the mass spectrometers mentioned above. Electron density altitude profiles were also obtained by several U.S. and Soviet spacecraft (e.g., Mariner 9), using the radio occultation technique. Thus, we have some information on both the dayside and near-terminator-nightside electron density values, covering the altitude range of about 120 to 300 km. No clear presence of an ionopause was seen in this database.

Climate

Climate encompasses a broad range of complex, interacting systems with a wide range of time scales. The Mars climate system, which includes the surface, atmosphere, polar caps, and accessible regions of the subsurface, has undergone significant change during the planet's history. Three time scales of climate variability can be considered: interannual, quasi-periodic, and long term.

Multidecade telescopic records of great dust storms, multiyear surface pressure records acquired at the Viking landing sites, multiyear orbiter observations of the appearance of the seasonal and residual polar caps, and large variations in atmospheric water make it clear that the climate of Mars exhibits distinct variations from one year to the next (interannual changes). Understanding the nature and causes of these variations is important for identifying interactions among the cycles of carbon dioxide, dust, and water in Mars's present climate.

One of the cornerstones of our understanding of the climate of Earth is that small, quasi-periodic variations in Earth's orbital and axial elements over time scales of tens to hundreds of thousands of years result in large-scale changes in Earth's climate.[23] Mars's orbital and axial elements experience variability on time scales that are comparable to those of Earth, but the magnitudes of these variations for Mars are significantly greater.[24] The consequent changes to the insolation at high latitudes undoubtedly have caused significant changes in the seasonal cycles of carbon dioxide, water, and dust. Based on our present understanding, Mars is the planet in the solar system that is likely to have experienced the most significant quasi-periodic variations in its climate (Figure 3.4).

A wide range of surface features on Mars can be interpreted as evidence for warmer climatic conditions at various times in the planet's history (long-term climate change). There is general consensus that Mars possesses all the volatile ingredients necessary to produce a warm and wet climate, but the problem is that at Mars's distance from the Sun, the stable location for Mars's volatiles is not in the atmosphere but in condensed phases, which makes it difficult to maintain a stable martian greenhouse.[25]

Although the earliest martian atmosphere was probably lost by impact erosion and hydrodynamic escape during the Early Noachian era, a relatively robust atmosphere appears to have been reestablished during the Noachian by primitive volatiles released during the creation of the Tharsis Plateau by volcanic and igneous processes. The end of the Noachian marked a huge change in the climate and probably in the volatile inventory of Mars. Erosion rates declined, valley network formation largely ceased, and magmatism declined. The intrinsic magnetic field appears to have declined or ceased at that time; the loss of the protective magnetic field may have allowed substantial solar-wind erosion of the atmosphere, with a consequent change in climate.[26]

Key Questions

Questions with potential for a paradigm-altering discovery related to water, atmosphere, and climate on Mars include the following:

- What are the sources, sinks, and reservoirs of volatiles on Mars?
- How does the atmosphere evolve over long time periods?

Questions with potential for a pivotal scientific discovery include the following:

- Is there an active water cycle on Mars?
- What are the dynamics of the middle and upper atmosphere of the planet?
- What are the rates of atmospheric escape?

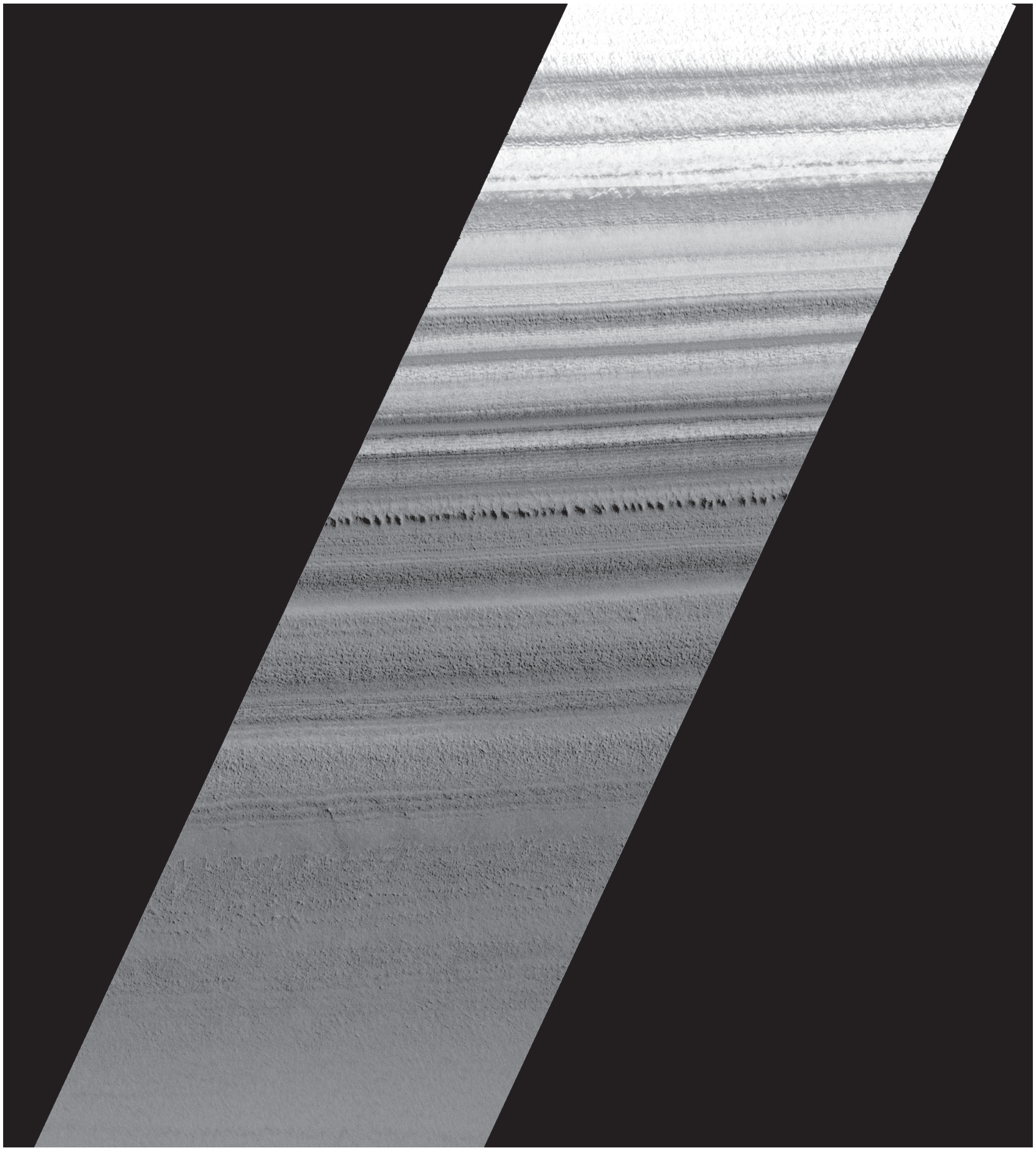

FIGURE 3.4 The Mars Orbiter Camera on Mars Global Surveyor imaged the alternating layers of bright and dark material comprising the North Polar Cap. This image of one of the dark lanes crossing the cap reveals internal layering. This layering is thought to consist of mixtures of water ice and dust, with the albedo variations indicating different dust concentrations in an ice matrix. The apparent regularity of the variations with depth may be indicative of quasi-periodic variations in the martian climate. The image (86.48° N, 279.54° W) shows a region 1.66 km wide, and the vertical relief from the top of the image to the bottom is approximately 350 m. MGS MOC, M0002100, courtesy of NASA/JPL/Malin Space Science Systems.

A question whose answer would contribute to building the foundation of knowledge of the solar system is—

- What is the three-dimensional distribution of water in the martian crust?

Future Directions

Important directions for the future relating to Mars's water, atmosphere, and climate are the following:

1. The ground-level chemical and isotopic composition of the atmosphere, including humidity, should be tracked for at least a martian year at a network of lander stations.
2. The distribution of water (in both solid and liquid form) in the crust, globally or at a wide variety of sites, should be established (e.g., by sounding radar).
3. The composition and dynamics of the middle and upper atmosphere and the rate of escape of molecules from the atmosphere should be measured.

STRUCTURE AND EVOLUTION OF MARS

Structure and Activity of the Crust and Interior

Major advances in our understanding of the interior of Mars have come recently in four important areas:

- The bulk composition of Mars is better constrained owing to a greatly improved estimate of the moment of inertia made possible by Pathfinder measurements.[27] The moment of inertia depends on the distribution of density within a planet, and only a limited range of rock compositions have a given density.
- Mars had a magnetic field in the past, but there is no present global field, as shown by high-amplitude magnetic anomalies detected in the southern highlands of Mars by the Mars Global Surveyor.[28]
- Crustal thickness variations are fairly smooth across the dichotomy boundary between the northern and southern hemispheres of Mars; thus, an impact origin for the low-lying northern hemisphere is not favored.[29] The crustal thickness results are consistent with a plate tectonic hypothesis, but they do not confirm that idea.
- A key insight from the MGS topographic data is that the Tharsis Plateau predates the formation of apparently fluvial channels. This suggests that the outpouring of lava to make the plateau may have released enough carbon dioxide to form an insulating atmosphere and sufficient water to form the channels and even an ocean.[30]

Composition of the Crust and Interior

Most of what we know about the composition of Mars comes from three types of measurements: (1) in situ analysis of the rocks and regolith by landers, (2) orbital observations by emission and reflectance spectroscopy, and (3) studies of meteorites that are inferred to have come from Mars.

In situ analyses by the Viking and Mars Pathfinder landers found rocks at the Pathfinder site to be more siliceous than the basaltic rocks at the Viking sites.[31] The soil is similar at both sites and less siliceous than rocks at either. Measurements from the Thermal Emission Spectrometer aboard MGS extended these compositions globally; andesitic rock appears to dominate in the northern lowlands and basalt in the older southern highlands.[32]

Members of the SNC category of meteorites, comprising the shergottites, nakhlites, and chassignites, plus the unique meteorite ALH84001, are thought to have come from Mars. Five different rock types are known in the SNC collection. They include basalts and lherzolites (shergottites), clinopyroxenites (nakhlites), a dunite (Chassigny), and an orthopyroxenite (ALH84001). Most appear to be igneous cumulates. None of these rocks matches the composition of the basaltic andesites found at the Mars Pathfinder landing site. Similarly, none samples the surface-atmosphere interface, and they constitute a very inadequate sample of interior compositions.

Chronology and Stratigraphy

The geologic units of Mars are assigned to three major time-stratigraphic systems. The oldest is the Noachian system, which comprises the ancient southern highlands. MGS data indicate that the Tharsis complex of volcanoes was initiated in the Upper Noachian era. Rocks of the Hesperian system overlie Noachian units; these include much of the northern lowlands. The most recent system is the Amazonian, represented by the plains and volcanic materials of Amazonis Planitia.

The absolute ages of Mars's geological events, and thus the time history of the planet's evolution, will be fully understood only when the relative chronology derived from stratigraphy is tied to an absolute chronology. The density of superposed craters provides a means of estimating absolute chronology, but this technique is dependent upon imperfect models of the cratering rate on Mars through time. The flux of cratering projectiles on Mars is uncertain by about a factor of two.[33] This uncertainty has relatively little effect on interpretation of the absolute age of Noachian terrains, expected to have been originally nearly saturated with craters, or of very young terrains, where a surface with a nominal age of ~10 million years is young in any case. However, the factor-of-two uncertainty means that ages of terrains that fall in middle martian history are very poorly constrained.

Isotopic dating of Mars rocks from key stratigraphic levels will be required to establish the absolute chronology of the martian geologic record. The most reliable dates will be obtained from samples returned to terrestrial laboratories; laboratory precision in ages gotten by the K-Ar, ^{39}Ar-^{40}Ar, Rb-Sr, Sm-Nd, and U-Th-Pb techniques will approach 10 million years. In order to extend the range of sites dated beyond those that can be reached by sample-return missions, it may be important to develop a technique of in situ dating, presumably by the K-Ar method, by robotic spacecraft. Using this method in the laboratory to date martian meteorite samples of known radiogenic age, researchers find that K-Ar can be used to date samples in situ to an accuracy of ~20 percent,[34] which for rocks of intermediate age would be a great improvement over the factor-of-two uncertainty in cratering chronology. Whether this technique can be effectively implemented on Mars has not been demonstrated.

Surface Processes

Water, wind, volcanism, and impact cratering have been fundamental drivers of large-scale surface modification on Mars. On a smaller scale, surface materials are altered by reaction with the atmosphere in ways that are poorly understood.

Morphologic features created by running water and, apparently, by standing bodies of water can be seen on Mars. Fluvial features range in size from the giant outflow channels to valley networks to recently identified small, young channels.[35] Features indicative of standing bodies of water range from putative shoreline features in the northern hemisphere, perhaps due to an ocean,[36] to deltaic and intracrater sediments, to finely layered bedding. Sediments deposited in standing bodies of water are high-priority sites for the preservation of fossils and biosignatures.[37] Many of the valley networks terminate in craters, while the outflow channels primarily debouched to the northern plains.

Wind has been a significant force in shaping the surface of Mars. Dunes are ubiquitous features, seen across Mars from orbiter to lander resolutions, while so much of the planet exhibits a mantle of fine-grained material that true bedrock exposures are rare. A better understanding of the importance of eolian processes through Mars's history will require thorough characterization of the current atmosphere and its dynamics, long-term surface observations of the surface and atmosphere at a range of sites, systematic imaging, and returned samples.

The style of volcanism varies in space and time across Mars, ranging from large constructs in the Tharsis region with relatively young surface flows (Figure 3.5), to vast Hesperian ridged plains, to morphologies suggestive of old, explosive volcanism in the central highlands. Our understanding of magma chemistry and absolute chronology is, however, primitive, and it is not yet clear whether the range in volcanic styles represents changes in source regions, changes in near-surface environments, or atmospheric evolution.

Models for the physical and chemical alteration of the martian surface span a wide range of possible mechanisms. The presence of an apparently deeply oxidized ancient crust coupled with apparently unoxidized later volcanic landforms has led to the idea that most of the weathering occurred early, during a warmer, wetter time,

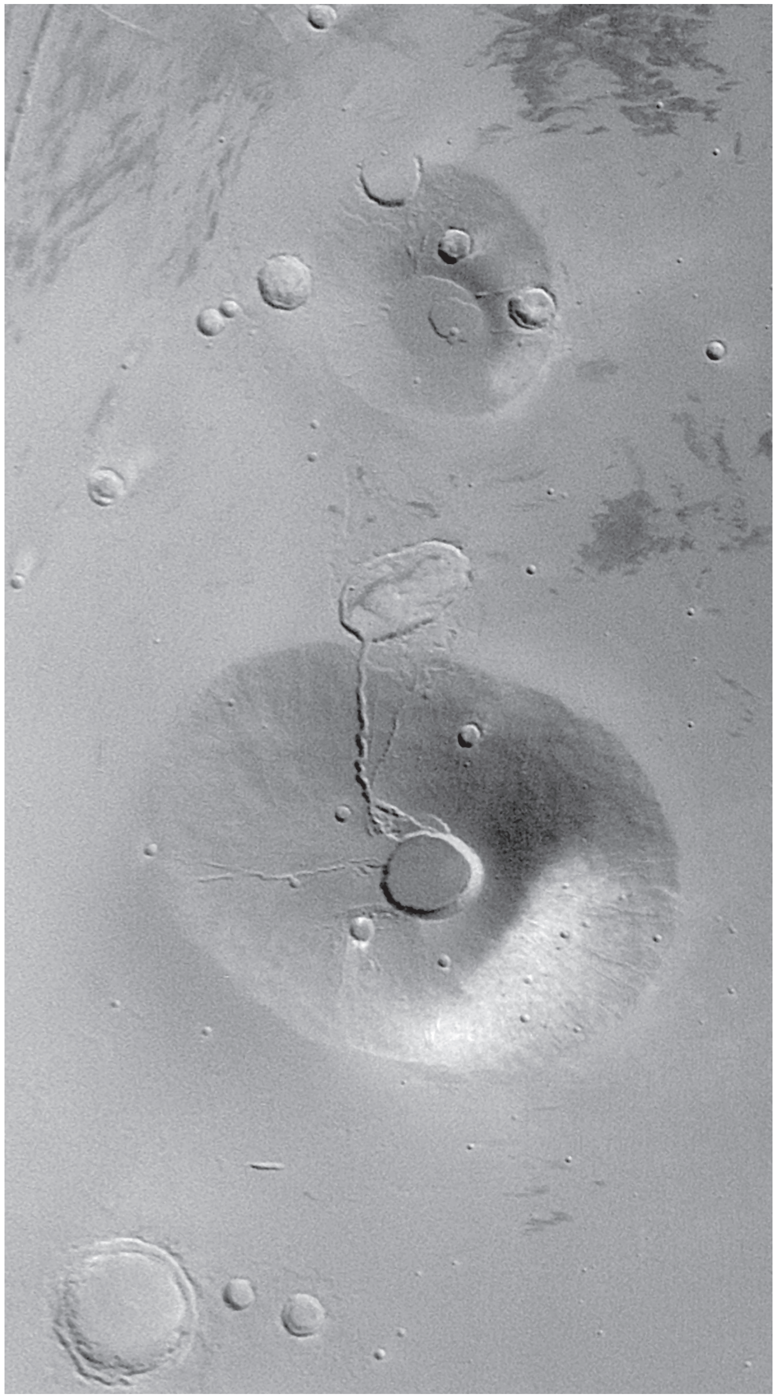

FIGURE 3.5 This wide-angle view from the Mars Orbiter Camera on Mars Global Surveyor shows the martian volcanoes Ceraunius Tholus *(lower)* and Uranius Tholus *(upper)*. The presence of impact craters on these volcanoes, particularly on Uranius Tholus, indicates that they are quite ancient and are not active today. The light-toned area on the southeastern face *(toward lower right)* of Ceraunius Tholus is a remnant of a once-more-extensive deposit of dust from the global dust storm events that occurred in 2001. The crater at the summit of Ceraunius Tholus is about 25 km across. Sunlight illuminates the scene from the lower left. Image courtesy of NASA/JPL/Malin Space Science Systems.

and that alteration has been sporadic since then. Estimated rates of weathering under current conditions are essentially negligible.

Key Questions

Questions with potential for a paradigm-altering discovery with respect to the structure and evolution of Mars include the folowing:

- What rock types comprise the crust of Mars?
- What are the nature and origin of Mars's crustal magnetism?

Questions with potential for a pivotal scientific discovery are as follows:

- What is the degree of internal activity in Mars?
- What is the size of the martian core, and is it partly or wholly liquid?
- What was the origin and fate of the Mars dynamo?
- What is the absolute chronology of the planet?
- How does the oxidation state of the Mars crust vary with depth?

Future Directions

Important directions for the future relating to Mars's structure and evolution include the following:

1. A long-lived network of seismic stations is needed on Mars for determining the structure, properties, and activity of its interior.
2. Heat flow from Mars ultimately should be measured at a series of surface stations.
3. The compositions and ages of crystalline rocks from a distribution of martian sites should be measured. This will best be done by studying returned samples, but the database can be expanded with in situ measurements made by landers.
4. A high-resolution magnetic map of Mars's southern highlands should be made.

INTERCONNECTIONS AND CROSSCUTTING THEMES

The fundamental questions for Mars exploration outlined in this chapter link strongly to the overall themes of this survey report as well as to the themes and directions of several of the other panels. Relative to the overall themes of the survey (Where did we come from? Where are we going? Are we alone?), the scientific and exploration priorities for Mars are strongly linked to the third question. However, it is impossible to properly address this question and understand the true meaning of an answer without a strategy for understanding the evolution of the interior and climate of the planet, which tie into the other survey themes.

A key crosscutting theme for "evolution of an Earth-like planet" is that of coupled atmosphere-surface-interior processes. The evolution of the climate is intimately tied to the release of volatiles from the interior and the protection of an early atmosphere by a magnetic field. As the climate evolves, its signature is recorded in minerals through surface-atmosphere interactions and preserved in weathering rinds and/or concentrated in sedimentary deposits. The isotopic signatures of current gaseous and solid phases, together with signatures preserved in the geologic record, document key elements of this evolution. This clearly cuts across the various themes of reports from this panel and the Inner Planets Panel.

The primary theme for the Inner Planets Panel is "The Inner Solar System: Key to Habitable Worlds." If we consider the solar system as a model for understanding how Earth-like planets form and evolve, then Mars, like each of the inner planets, is a critical piece of the puzzle. Through the exploration of the inner planets and comparative planetology, we have developed a deeper understanding of the similarities and differences in planetary evolution and relationships to the basic physical and chemical properties of the planets. Yet we are still faced with fundamental questions, such as, What led to the unique character of our home planet? How important is relative position in the solar system, or even birth order? What is the real role of planetary size? Why is plate tectonics observed only on Earth? How does a magnetic field affect climate and volatile evolution? How does the presence of a biosphere affect planetary evolution? (We know Earth's biosphere controls the composition of its atmosphere. Comparisons of Venus with Earth underline the difference that this can make.)

The exploration of Mars will feed directly into the major questions defined by the Inner Planets Panel. However, a detailed Mars program is not a substitute for the exploration of the inner planets; Mars is but one "leg of the stool." Just as we cannot truly understand the ramifications and implications of the answer to the question, Did life ever evolve on Mars?, without a comprehensive knowledge of the planet's evolution, so also we cannot address the fundamental questions of the inner solar system without comprehensive knowledge and comparative study of all the planets.

CURRENT NASA AND INTERNATIONAL PLANS FOR MARS EXPLORATION

The pace of Mars exploration for the next decade is breathtaking. A recently released report by the NRC's Committee on Planetary and Lunar Exploration (COMPLEX), *Assessment of Mars Science and Mission Priorities*, reviewed the current state of Mars science, identified critical questions for future investigation, and mapped the congruence between existing and proposed missions and these science priorities.[38] The results are summarized in Table 3.1.

Two important points are evident from this summary. The first is that, including spacecraft currently in orbit around Mars and excluding the Mars Sample Return mission, there are nine missions planned or in operation, some involving multiple assets such as the two Mars Exploration Rover (MER) missions and four landers for NetLander, that will fly before the end of 2009.[a] In addition, a Mars Scout mission will be selected before the end of 2003 to fly in 2007. The range of Mars science that will be addressed by these missions is as broad and deep as the Mars science community, ranging from the upper atmosphere to the deep interior. The second point, however, is that even with this program, there are areas of science that will not be addressed. For example, no plans have been made for conducting absolute dating of the surface by isotopic techniques; nor are there plans to investigate surface-atmosphere interactions in the polar regions.

It has been argued that in order to properly address the highest-priority question for Mars—Did life ever evolve on the planet?—the planetary context is crucial to understanding the implications of a yes or no response. Given the range of investigations over the next decade, this foundation should be achieved. However, within a fiscally constrained program it is still not possible to cover every topic to the level expected by every constituent.

KEY MEASUREMENT OBJECTIVES

On the basis of the current state of Mars science reflected in this chapter as well as in other recent NRC and NASA documents,[39,40] the most important measurement objectives for Mars have been identified and prioritized. The top priority is to obtain data to answer the question Did life ever arise on Mars? This panel concurs with the conclusions of earlier NRC panels that a definitive answer to this question can only be obtained via the study of samples returned to Earth.[41] Returned samples would also serve to support a number of other high-priority studies bearing on the climate and weathering history and geologic evolution of the planet.

To understand the overall evolution of Mars and the interconnections among its systems (interior, surface, atmosphere), which are central to answering the question about life on the planet, key in situ measurements are required. The atmospheric and seismic measurements described above (see the sections "Water, Atmosphere, and Climate on Mars" and "Structure and Evolution of Mars") require landers with long-duration capabilities to establish the presence of internal activity and capture the full seasonal dynamics of atmospheric processes. The

[a]Editor's note: During the period when this report was being prepared for publication, the French-led NetLander mission was canceled.

TABLE 3.1 Comparison of Recommendations of Science Priorities with Experiments on Projected Flight Missions

	Panel Recommending											Inclusion in Missions									
												NASA						Other			
Science Priorities	COMPLEX 1978	CPBCE 1990	COMPLEX 1990	COMPLEX 1994	NASA 1995	COMPLEX 1996	McCleese 1996	COMPLEX 1996	COMPLEX 1998	NASA 2000	MEPAG 2000	MGS 1997	MO 2001	MER 2003	MRO 2005	MSL 2009	Sample Return	Nozomi 1999	Mars Express 2003	Beagle 2 2003	NetLander 2007
Interior																					
What is the size and state of the core?	●		●	●							●										●
Is Mars active (interior activity, tectonics, volcanism)?				●							●										●
What is the thickness/structure of the crust?	●		●							●	●	○									
What is the geothermal gradient?	●										●										
What is the character/origin/evolution of the magnetic field?	●		●								●	●									○
Geochemistry and Petrology																					
What variations of geochemistry and petrology are present?	●												●			○	○		●		
What have been mechanisms of geochemical differentiation?		●															○				
Is there evidence for aqueous mineralization?					●								○	○	○	○	●		○	○	○
Chronology and Stratigraphy																					
What are the relative ages of geological units and events?	●	●									●	○	○		○						
What are the absolute ages of geological units and events?	●	●									●									○	
What are the absolute ages of crystalline rocks?	●										●						●			○	
Surface Processes																					
What are the present rates of erosion and deposition?											●	○	○		○				○		
What were the past rates and processes: water and eolian?	●											○	○		○				○		
What has the role of impact cratering been?												○	○		○				○		
What role has volcanism played in surface evolution?											●	○			○				○		
Surface/atmosphere interaction: what volatile sources/sinks?	●										●	○	○	○	○	○			○	○	○
Water																					
Present cycle: sources, sinks, mechanisms, dynamics?	●						●			●					●				●		
What is the 3-D crustal water distribution/origin (liquid/ice)?	●						●			●	●	○			○				○		○
How has the hydrological cycle operated in the past?		●					●				●	○			○						
Life																					
Does life exist on Mars?	●										●					○	●				
Can any chemical products of life be detected?	●		●		●		●				●			○	○		●				
Do isotopic patterns suggest life?							●				●						●				
What can we learn from Antarctic meteorites?						●															
Atmosphere																					
What is the current composition of the atmosphere?	●										●				○				○	○	
What are the circulation dynamics of the atmosphere (T, P)?	●			●			●					●			○				●	○	●
How has the atmosphere changed over time?											●										
What is the radiation environment at the surface of Mars?													●				●				
What is the nature of weather on Mars?	●			●				●			●				●				●	○	●
Climate Control																					
What is the interannual variability of climate?				●							●				○				○		○
What has been the long-term climate history of the planet?											●										
Upper Atmosphere and Plasma Environment																					
What are the dynamics of the upper atmosphere?																					
What are the hot atom abundances and escape fluxes?											●							○	○		
What are the ion escape fluxes?																		○	○		
What are the magnetic field configurations?	●			●														○			
What are the processes controlling the ionospheric energetics?																		○			

NOTE: In the column titled "Panel Recommending," solid circles identify the questions that each panel recommended for study. The column labeled "Inclusion in Missions" shows which missions will address these questions; solid circles signify missions that will concentrate on each science objective, and open circles signify a lesser level of attention to that objective. Missions in NASA's Mars Exploration Program are listed separately from the missions projected by other nations. During the period when this report was being prepared for publication, the French-led NetLander mission was canceled.

dynamics of the upper atmosphere of Mars and rates of atmospheric escape should be studied (among other reasons) to constrain the rates of water loss from Mars, a key factor in the volatile history.

In summary, the measurement objectives that the Mars Panel has identified include the following:

- Definitive measurements to test for the presence of extant or extinct life, or the geochemical and organic chemical evidence for past biological activity. These measurements will require highly sophisticated equipment, procedures, and sample preparation techniques not currently available, nor likely to be available in the foreseeable future, for in situ experiments. Consequently, samples selected from well-documented sites of promising biological potential must be returned to Earth for detailed study.
- Detailed characterization of the geochemistry, mineralogy, trace elements, and chronology of samples selected from well-documented locations and returned to Earth to address questions relevant to the absolute chronology, climate and water history, igneous and metamorphic evolution, and weathering history of Mars.
- Determination of the sources, sinks, and reservoirs of volatiles through integrated measurements of the composition of the atmosphere (including humidity), isotopes of atmospheric gases, and volatile content of and processes in the subsurface, made over at least 1 martian year, using long-lived gas analyzers. Concurrent measurement of the composition of the middle and upper atmosphere is required to provide a systematic understanding.
- Determination of the size of Mars's core, its current internal activity, and its large-scale planetary structure using passive seismometry at a minimum of four sites, operating for at least 1 martian year.
- Determination of the absolute chronology of Mars. Required are the measurement of ages of crystalline rocks from surfaces on at least four strategically chosen geologic units displaying conspicuously different crater densities. This measurement objective can be achieved through sample return if appropriate surfaces are sampled, and/or through in situ age determinations made by landers if the technology can be demonstrated to achieve sufficient precision and accuracy.
- Measurements from orbit of the dynamics of the middle and upper atmosphere of Mars and the rate of atmospheric escape.
- Measurements of the current neutral gas and ion escape fluxes; both optical remote-sensing and in situ instruments carried on an orbiter are required to achieve these objectives.

SUGGESTED MISSIONS

Mars Sample Return

The Mars Panel attaches the greatest importance to Mars Sample Return (MSR), unquestionably a high-cost mission. While MSR cannot replace certain crucial in situ measurements (e.g., heat flow, seismicity, electromagnetic sounding for water, analyses of labile samples, and determination of atmospheric dynamics), it is scientifically compelling in its own right, and the ground-truth acquired from returned samples will aid the interpretation and greatly enhance the value of data from orbital and robotic lander missions. Spacecraft capabilities that would contribute to effectiveness in sampling include mobility, in situ reconnaissance analytical instrumentation, and a core drilling device. (Under current conditions, it appears likely that living organisms, and more generally all organic material, would be destroyed by oxidizing conditions in the surface layer of Mars. They may be preserved only at depth in the planet. Just what depth—centimeters, meters, kilometers—is unknown.) Necessary capabilities include the ability to manipulate and document samples collected and to package them in a way consistent with requirements placed by the planetary protection protocol imposed on the mission. A radioisotope power system for the mission (see below) would expand the geographic range of sites that could be sampled and would extend the mission's stay time, allowing the collection of a larger and more carefully selected suite of samples. Ample power undoubtedly will be important if drilling is contemplated.

It is essential that the site to be sampled be carefully chosen, with the choice drawing upon the large body of orbital and lander data that will be in place by the time the MSR is flown. However, no single sample-return mission will completely satisfy the need for this form of exploration, no matter how carefully it is planned. Mars is highly varied in its geology; prior to returning some martian material to Earth it may be impossible for us to understand which type of site has the highest potential for providing samples that contain evidence of life and other valuable scientific data; sample collection and return represent a new endeavor, one that may not work perfectly the first time. It will be necessary to plan for a series of MSRs over whatever span of time the budget permits.

Mars Long-Lived Lander Network

The Mars Panel also recommends the emplacement of a network of long-lived surface stations on that planet, a moderate-cost mission. The primary purpose of these stations should be to address two questions that the panel believes are neglected by the Mars Exploration Program as currently constituted: (1) the internal structure and activity of the planet and (2) the composition and activity of its atmosphere. Such a mission, or series of missions, has not been designed by NASA, but the French space agency Centre National d'Etudes Spatiales (CNES), in cooperation with international partners, is planning a four-station network science mission with goals that are compatible with the panel's recommendations. Radioisotope power systems will be required to achieve the needed lifetimes and global distribution of the stations.

The Mars Long-Lived Lander Network (ML^3N) would use passive seismometers to explore the structure and activity of Mars. Heat-flow probes also would contribute importantly to our knowledge of the martian interior, but these require the drilling of holes, and they might more logically be emplaced by MSR if that mission has drilling capability; this would avoid placing a drilling requirement on the lander network.

ML^3N should also include meteorological stations that measure pressure, temperature, relative humidity, atmospheric opacity, and wind velocity. Also included should be mass spectrometers that permit high-precision, long-lived chemical and isotopic atmospheric analysis of the chemical dynamics of C, H, and O at Mars's surface. Time variability of isotopic compositions can be interpreted in terms of sources, sinks, and reservoirs of volatiles, and atmospheric evolution. Humidity sensors would track the flux of water vapor into and out of the regolith with time of day and season, providing important insight into the water budget on Mars.

The complement of instruments on the French-led NetLander mission, the four landers distributed around the planet, and the expected lifetime of 1 martian year will be sufficient to constrain the nature and size of the core, seismic activity, seismic velocities of the crust and mantle, and atmospheric properties of pressure, temperature, humidity, and wind speed. They will also have a magnetometer and electromagnetic sounding capabilities to sense crustal structures and to search for subsurface water and ice. While this complement of instruments does not address all of the high-priority goals outlined for the ML^3N, it represents a significant step forward.

Mars Upper Atmosphere Orbiter

The need for an orbital mission to study the upper atmosphere of Mars is identified above (see the section "Key Measurement Objectives"). Areas to be addressed by this low-cost mission are the dynamics of the upper atmosphere; hot atom abundances and escape fluxes; ion escape; minimagnetospheres and magnetic reconnections; and energetics of the ionosphere. A Mars Upper Atmosphere Orbiter (MAO) can explicitly explore these issues in the present-day environment and answer a number of important scientific questions. Furthermore, such a mission could quantify present-day escape processes and allow certain backward extrapolations to earlier epochs in martian history.

The instruments needed for a meaningful attack on these questions would require no new, basic instrument development and could be installed as a partial payload complement of an orbiting spacecraft. The neutral winds can be measured by either a "baffled" neutral mass spectrometer or a Fabry-Perot interferometer. The latter instrument, along with a good ultraviolet spectrometer, could address in a meaningful way the hot atom and neutral escape flux questions. The neutral mass spectrometer would also provide neutral composition and temperature information. A plasma instrument complement consisting of a magnetometer, low-energy ion mass spectrometer (capable of measuring flow velocities and temperatures), an electron spectrometer, a plasma wave detector, and a Langmuir probe would go a long way toward resolving the questions of ion escape, minimagnetospheres and magnetic reconnections, and energetics of the ionosphere.

Mars Science Laboratory

The Mars Exploration Program (MEP) projects development of a Mars Science Laboratory[b] (MSL), presumably a moderate-cost mission, for launch in 2009. Its instrument payload has been stated only in the most general terms. The mission may be important, indeed essential, as a technology-demonstration precursor mission to MSR.

Mars Scout Missions

The Mars Scout program consists of competed, Discovery-class, principal-investigator-led missions with $300 million cost caps. The program was instituted by NASA to meet science goals and opportunities not covered by other missions and to provide a mechanism for the MEP to be responsive to discoveries. As structured, the Scout program provides an excellent opportunity for NASA to accommodate science topics outside the principal objectives of the MEP, and for the broad science community to respond to discoveries and technological advancement. The Mars Panel strongly endorses NASA's desire to structure the Scout program after the successful Discovery program. In that regard, it is essential that the measurement goals for the Mars Scout program be directed toward the highest-priority science for Mars and be selected by peer review. As witnessed by the response to the recent call for Scout proposal ideas (more than 40 submissions were received), tremendous enthusiasm has been stimulated by recent Mars discoveries for addressing scientific investigations not covered by the MEP. Scout provides for the MEP a component that is highly flexible and responsive to discovery, and the panel recommends that Scout missions be flown at every other Mars launch opportunity. Some of the mission priorities defined in this chapter (e.g., the ML^{3}N and MAO missions) could be accommodated in the Scout program as stand-alone missions or as targets of opportunity on international missions. The science priorities outlined in this chapter do not encompass the full range of science topics of great importance to Mars that may fit within the Scout funding and mission profile. These are covered more completely in the NRC report *Assessment of Mars Science and Mission Priorities*,[42] as well as in the recent report of the Mars Exploration Payload Assessment Group (MEPAG).[43]

IMPACT OF SAMPLE RETURN ON THE MARS EXPLORATION PROGRAM

One of the major problems facing the MEP is choices. The abundance of new data across all disciplines has led to extraordinary discoveries about Mars that are being reported in rapid succession, and with the planned program of NASA and international missions, this is likely to continue (see Table 3.1). The compelling nature of the planet and this vigorous exploration program has spawned a deep and broad scientific community whose interests and compelling questions span many orders of magnitude in space and time. Yet despite the apparent richness of this exploration program, the resources for NASA's MEP are nevertheless finite. The scientific community and NASA are therefore faced with the critical question of prioritization.

Central to this debate is the question of sample return, on which there are two points of view. The first view is that the costs of sample return will be high in terms of the spacecraft resources and infrastructure needed to handle, house, and analyze the samples. This investment will undoubtedly defer in situ and orbital investigations of Mars during this effort. This view further advocates that because of this cost, sample return should be delayed until such time as the science questions to be addressed by sample return are so compelling and the technology so mature that success is assured. As the program moves forward then, the MEP resources should be directed toward continued in situ and orbital investigations. For example, the current best estimates of the cost of sample return range between $1.5 billion and $2.5 billion, which would require NASA to combine the resources from two launch opportunities to fit within the MEP cost profile.

It could be argued that for these same resources, four landed science packages with rovers could be sent to some of the many interesting places on Mars, to conduct in situ surface science and life-detection experiments and to establish well-instrumented stations for interior, climate, and meteorology studies. This view that sample return should be delayed is motivated in part by a fear that if sample return is approached too quickly, then all Mars

[b] Also known as the Mars Smart Lander or the Mobile Science Laboratory.

science will be arrested to achieve this goal, and if the first samples are indistinguishable from SNC meteorites, further support for Mars exploration will be jeopardized.

The contrary view is that the most compelling question for Mars exploration, and one that is central to the SSE Survey, is Are we alone?, and that only through the analysis of samples returned to Earth can this question be addressed to any level of certainty. This view also holds that the breadth of Mars science to be addressed by the upcoming missions (see Table 3.1) is enormous and will do much to provide the essential context to address this question. However, the next leap in understanding Mars will only be achieved though the analysis of samples from the surface understood in a planetary context. This view also holds that the first sample return will neither address all questions nor close the book on the life question. However, it will be critical for making the maximum use of the huge investment in data sets made over the preceding decade (such as shown by the lunar example). Subsequent sample-return missions, interleaved with appropriate orbital and in situ exploration, will ultimately drive exploration to the sites that will maximize our understanding of Mars and answer the question Are we alone? This view is motivated in part by the sense that sufficient information exists today to move toward the goal of sample return and that the technological challenges are sufficiently large that the program needs to begin now in order to achieve a launch early in the next decade (2013-2020), and by a fear that without a clear commitment to sample return the MEP will never achieve this goal and will lose support.

The choice of which path to take is not necessarily an either-or proposition. The true costs of sample return are not yet known and will be refined over the next few years. Even with a high cost, there will be abundant other opportunities for Mars exploration. For example, following the flight of Mars Science Laboratory in 2009, the next opportunities to fly to Mars are in 2011 and 2013. If the costs of a simple sample-return mission come in at the low end of the cost estimates ($1.5 billion) and it is flown in the 2013 opportunity, then, according to recent reports of the MEP budget to MEPAG, there should be sufficient resources to fly a competed Scout mission for the 2011 opportunity. If the costs for sample return are too high to bear for the 2013 opportunity, this could be delayed till the 2016 opportunity, and MSR together with competed Scout missions in 2011 and 2013 would easily fit within the current budget climate.

RECOMMENDATIONS OF THE MARS PANEL TO THE STEERING GROUP

Mission Priorities

Mars Sample Return

The Mars Panel attaches the highest priority to missions that will collect samples on Mars and return them to Earth, beginning at the 2011 opportunity if this is possible. Observations made by robotic orbiters and landers beyond 2005 cannot alone answer the most important questions regarding Mars: whether life ever started on that planet, what the climate history of the planet was, and why Mars evolved so differently from Earth. The definitive answers to these questions will come from the study of Mars samples, in the context of orbital and surface in situ measurements, of known provenance in laboratories on Earth.

The Need for Sample Return—The Search for Life. At our present state of knowledge and technological expertise, and probably for the next several decades, it is unlikely that robotic in situ exploration will prove capable of demonstrating to an acceptable level of certainty whether there once was or is now life on Mars. Results obtained from any life-detection experiment carried out by robotic means are likely to be ambiguous for these reasons:

- Results interpreted as showing an absence of life will be challenged because the experiments that yielded them were too geocentric or otherwise inappropriately limited;
- Results consistent with, but not definitive of, the existence of life (e.g., the detection of organic compounds of unknown, either biological or nonbiological, origin) will be regarded as incapable of providing a clear-cut answer; and

• Results interpreted as showing the existence of life will be regarded as necessarily suspect, since they might reflect the presence of earthly contaminants rather than of an indigenous martian biota.

Similarly frustrating results can be expected in attempts to search robotically for either of the two categories of fossil life that might be preserved on Mars: stromatolites and microfossils. Stromatolites are accretionary organosedimentary structures, commonly thinly layered, produced on Earth by the activities of mat-building communities of mucilage-secreting microorganisms. Unfortunately, true stromatolites on Earth can be confused with nonbiologically deposited look-alikes (e.g., in thin, sometimes wavy layers of mineral precipitates commonly found in caves and hot spring deposits on Earth; on Mars, such deposits may have been laid down, for example, by repeated wetting and drying or freezing and thawing of mineral-charged salt pans or shallow lagoons). If stromatolite-like structures were photographed on the surface of Mars, it seems certain that there would be widespread uncertainty as to whether the objects detected were in fact produced by life. Similarly, it seems unlikely that robotic detection of objects resembling microfossils in or on the surfaces of rocks on Mars would prove sufficiently convincing to demonstrate to an acceptable level of certainty that past life existed on that planet.

The Need for Sample Return—Geochemistry. In the area of geochemistry and mineralogy, thin sections of returned samples can be prepared in terrestrial laboratories and studied by microbeam techniques as well as optically. Rocks contain a near-infinite amount of information on a microscopic scale, some of it crucial to an understanding of the rock's origin and history. Rocks can be disaggregated, and their constituent minerals can be studied chemically and isotopically. The data obtained provide strong clues about and constraints on the nature of the differentiation events that led to the formation of the rock. They also make possible a variety of approaches to precisely dating igneous rocks in the sample collection. Information about the Mars climate will be found in the layer of weathering products that are expected to be found on rock samples. These products will almost certainly be very complex minerals or amorphous reaction products that will tax the best Earth-based laboratory techniques to understand. It is very unlikely that anything but a highly qualitative and ambiguous description of the weathering products could be made by robotic instruments operating on the martian surface.

The Need for Sample Return—Climate and Coupled Atmosphere-Surface-Interior Processes. Some surface-atmosphere and climate processes involving labile elements or compounds must be studied in situ. Nevertheless, the key measurements for understanding the relative loss of portions of the atmosphere to space and to surface reservoirs are the compositions of surface minerals and their isotopic systematics. Atmospheric-loss processes (e.g., hydrodynamic escape, sputtering) leave characteristic isotopic signatures in certain elements. Loss to space versus to surface weathering (e.g., CO_2 to carbonate minerals) is likely to produce isotopic fractionation in different directions. The ratio of ^{15}N to ^{14}N in the martian atmosphere is understood to have evolved over the past 3.8 billion years (it is currently 1.6 times the terrestrial value), and a determination of this ratio in near-surface materials may constrain the time of their formation. Compositional and isotopic analysis of surface minerals, weathering rinds, and sedimentary deposits will establish the role of liquid water and processes such as weathering. The corresponding measurements on volatiles released from near-surface materials are likely to be more heterogeneous and may provide fossils of past atmospheric and chemical conditions that allow the past climate to be better understood.

Martian Meteorites—Not a Substitute for Sample Return. The SNC meteorites do not obviate the need for sample-return missions. SNC meteorites have provided a tantalizing view of a few martian rocks and a demonstration of how much can be learned when samples can be examined in Earth-based laboratories; however, they represent a highly selected subset of martian materials, specifically, very coherent rocks of largely igneous origin from a small number of unknown locations. Thus, SNC meteorites are unhelpful in answering one of our outstanding questions—What is the absolute chronology of Mars?—because although they can be accurately dated, the geologic units from which they are derived are unknown. While returned samples are also a selected subset of martian materials, their geologic context will be known, and they will be from sites selected because they can provide particularly valuable information.

Regarding the climate history of Mars and possible life there, the samples that will provide the most information are not igneous rocks, as the SNC meteorites are, but sediments and soil samples. Taking Yosemite Valley as a terrestrial analog, the SNC meteorites represent the cliffs rather than the river muds and the sediments from the outwash stretching into California's Central Valley. It is the latter materials that can provide information about chemical conditions, biological processes, and timing; their martian analogs, geologic features that have the properties of river and lake deposits, will help most in understanding water and life on that planet.

Mars Long-Lived Lander Network

The Mars Panel considers that the ML^3N should be the second-priority Mars mission. The principal experiments on these landed stations should be passive seismometers and analyzers of the ground-level atmosphere, both of which must continue to record data for at least a year to achieve their potential. Earlier NASA advisory panels consistently recognized the importance of these experiments and recommended their implementation.[44]

Seismic data can determine the size of the core, which will constrain the bulk composition of the planet, as will information on the seismic velocities in the mantle. Knowing the bulk composition of Mars is important for understanding the origin of the planets. Seismology can tell us whether the core is all solid, all liquid, or part solid and part liquid (as is Earth's core), which has a direct and profound bearing on our understanding of planetary dynamos and the present-day lack of a Mars global magnetic field.

In the area of martian atmospheric science, there are open questions of meteorology, atmospheric origin and evolution, chemical stability, and atmospheric dynamics. These questions are of particular interest for a broad community of scientists, because useful comparisons with Earth can be made that may prove important for understanding the atmospheric evolution of both planets.

The Mars Panel attaches high priority to a better understanding of the martian atmospheric composition, chemistry, circulation, and concentration of near-surface water vapor as the key components of climate systems and for comparative studies of atmospheric dynamics and evolution.

Mars Upper Atmosphere Orbiter

The third priority of the panel is given to the Mars Upper Atmosphere Orbiter mission. The upper atmosphere of Mars drives the lower atmosphere in a variety of ways, and very little information is available on the martian upper atmosphere. There are no existing plans in the current U.S. Mars Exploration Program to address any of the scientific questions that are listed above concerning the upper atmosphere of Mars (see the subsection "Mars Upper Atmosphere Orbiter"). Japan's Nozomi and Europe's Mars Express will address these questions to some extent, but much more data will be needed to meaningfully elucidate these open issues. Both the Nozomi and Mars Express will arrive at Mars during solar cycle minimum conditions, and data from solar cycle maximum are required in order to answer some of the outstanding questions (e.g., nonthermal escape).

Unprioritized Missions

Mars Science Laboratory

The MSL mission may be important, indeed essential, as a technology-demonstration precursor mission to MSR, but the panel saw little science for MSL that cannot be done as well or better by the missions discussed above. The detailed examination and analysis of rock samples can be done far more capably in terrestrial laboratories (though admittedly MSL could perform simpler analyses of a larger and more dispersed set of samples than those that an MSR mission could return). The ML^3N mission could conduct much more comprehensive atmospheric and seismic studies than could MSL, which is a single mission, not a network. K-Ar ages remotely measured by MSL, if this technique can be made to work, will provide only one data point toward calibrating the martian geological column, with accuracy inferior to that obtained on MSR samples in terrestrial laboratories.

Since the panel's task was to prioritize science missions and since it sees MSL largely as a technology-demonstration mission, it has not included MSL among the prioritized missions.

Mars Scout

The program of Mars Scout missions provides an excellent opportunity for NASA to accommodate science topics outside the principal objectives of the Mars Exploration Program and for the broad science community to respond to discoveries and technological advancement. If this activity is to be modeled after the successful Discovery program, it is essential that the science goals for Mars Scout missions be directed toward the highest-priority science for Mars selected by peer review.

There is concern in the Mars science community that Scout missions may be vulnerable to being sacrificed in times of budget stringency. The panel urges that the Mars Scout program be maintained with a high level of protection.

Technology Development

Sample return will not be a simple task, and it has not been achieved by a robotic mission other than the Russian sample return from the Moon 30 years ago. For the much more difficult sample return from Mars, many technologies will have to be developed, tested, and validated. These include hazard avoidance in landing, sample selection, handling and delivery to the transfer chamber, the Mars Ascent Vehicle, orbit rendezvous and capture, transfer to Earth, and quarantine on Earth. It will be essential for precursor missions to MSR to incorporate the testing of essential technologies.

Sample return and a long-lived surface network will require sophisticated instrumentation for science and operations. While much thought has been given to what sort of instruments might be required, there has been less direct investment in the development of instruments and demonstration of the technology required for flight-qualified systems.

An extremely important consideration in establishing the capabilities of landed packages on Mars, static or roving, is the power supply on which they rely—the options being solar panels and radioisotope power systems (RPSs). The Viking landers lasted as long as 7 years because they had RPS power. The twin MER 2003 rovers, with solar panels, will operate for no longer than an estimated 90 days. This is because as the elevation of the Sun changes, the available solar power decreases; for the same reason, the rovers get colder and need more power to keep warm. Meanwhile, dust is accumulating on the panels, further reducing the power. The MER rovers are also restricted by the needs of their solar panels to land in the 10° N to 15° S latitude belt at relatively low elevations.

The ML^3N described above will not be able to operate within these constraints; an RPS will be essential. The power problem will seriously affect sample-return missions as well. Reliance on solar power would mean that samples will almost certainly have to be collected at low latitudes, which excludes those parts of Mars where ground ice is stable and where other volatiles are most likely to be present. If the sample-return mission has a rover to collect samples, its lifetime will be short. The use of a drill to collect samples would require a generous supply of power.

Data Analysis, Ground-Based Observations, and Laboratory Studies

The Mars Exploration Program, with its missions at 2-year intervals, presents a new problem in fully exploiting the amount and variety of data that will be collected. The volume and quality of data returned by MGS alone have been extraordinary, and the analysis of these data is only beginning. With the rapid pace of Mars missions planned for the next decade, the flood of data can be expected to increase.

While the Mars Exploration Program consists of flight missions, exploration and understanding of the planet as a system also depend on other modes of data acquisition. Some examples follow.

Telescopic Studies

Continuing telescopic observation of Mars has played a key role in demonstrating that the surface of Mars changes on a relatively short time scale (as with seasonal changes, dust storms, evolution of the polar caps.) Telescopic and spacecraft data are highly synergistic, and each plays a role in supporting the other. Support for future robotic and possible manned missions to Mars will require a long climatological baseline. The long baseline, partially obtained with ground-based and HST telescopic data, will also contribute to an understanding of the water cycles between the atmosphere, regolith, and polar caps, as well as spatially resolved data on volatile cycles of water, carbon dioxide, carbon monoxide, and ozone.

Theoretical Models

Models are an essential component of any scientific endeavor. Examples of theoretical planetary studies are those that treat the geodynamics of Mars, its interior structure, atmospheric loss and fractionation, and global climate and general circulation models.

Martian Meteorites

As already mentioned, the SNC category of martian meteorites plays an important role in studies relating to martian life and the planet's structure and evolution. Studies of this small group of meteorites in terrestrial laboratories have provided invaluable, if fragmentary, information about the geochemistry and chronology of Mars. NASA, the National Science Foundation, and the Smithsonian Institution have jointly supported an Antarctic meteorite program since 1976, in which teams of experts search areas known to contain a concentration of meteorites for 6 weeks every austral summer; support of this program should continue.

Astrobiological Research

Studies of deep-sea hydrothermal environments, hot springs, the deep subsurface, alkaline or acidic environments, and sea ice have revealed amazing microbial diversity in the form of uncultured organisms from environmental extremes. Some of these habitats are potential analogues to past and present martian environments where life may have arisen or might continue to exist. Through expanded knowledge about the potential diversity of the microbial world, we can explore how ancient microbial life might have impacted planetary processes on Mars.

Preparations on Earth for Sample Return

A series of NASA and NRC panels have considered the special problems associated with bringing samples from Mars to Earth,[45-49] and NASA has acknowledged the need to prevent forward and back contamination at every stage of the process of delivery. This includes the need to construct a quarantine facility to receive and contain the samples.

A recent NRC report drew attention to the long lead time required to prepare a Mars Quarantine Facility (MQF) for the reception of Mars samples once they are delivered to Earth.[50] On the basis of prior experience with terrestrial biocontainment facilities and the Apollo Lunar Receiving Laboratory, the authoring committee estimated that 7 years would be required to design, construct, and staff the MQF. To this must be added the time needed to clear an environmental impact statement and to carry out several NRC recommendations for reconnaissance studies that are needed to inform the design and operation of the MQF.[51] The aggregate of time required will strain the schedule even of a 2011 launch (2014 return). It is important that scientific research and design studies that must precede the design and construction of a Mars Quarantine Facility begin immediately, and design and construction of the facility should begin at the earliest possible time.

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